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Micronavigation of the Klein 5500 sidescan sonar using inter-ping beam correlations

John A. Fawcett

Defence R&D Canada

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Abstract

In this report, the cross correlation between the beams of sidescan sonar data from consecutive pings is investigated. The along-track and across-track shifts which maximize this cross-correlation yield high resolution estimates of the along-track motion and the sway of the towfish. The difference of the estimates for the port and starboard sides can be used to estimate the towfish heading change. This technique is examined using data from the DRDC Atlantic Klein 5500 sidescan sonar and it is shown that the estimates, which are obtained in this manner, are consistent with direct sensor measurements of the towfish heading and pitch.

Résumé

Dans le présent rapport, on étudie la corrélation croisée entre les données relatives à la direction transversale du sonar à balayage latéral obtenues avec des impulsions consécutives. Les décalages longitudinal et transversal qui donnent une valeur maximale de cette corrélation croisée fournissent des estimations à haute résolution du mouvement longitudinal et du balancement du poisson. La différence entre les estimations pour le côté bâbord et le côté tribord peut être utilisée pour évaluer le changement de cap du poisson. On examine cette technique en se servant de données du sonar à balayage latéral Klein 5500 de RDDC Atlantique, et on montre que les estimations obtenues par cette méthode sont compatibles avec les mesures directes du cap et du tangage du poisson réalisées à l'aide de capteurs.

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Executive summary

Background:

In order to very accurately geocode sidescan sonar data it is necessary to have precise measurements of the sonar towfish motion. In the case that one wishes to combine beam or stave information from successive pings in a coherent fashion (for example, synthetic aperture processing) , then very accurate measurements of the towfish motion are also required. In this report we investigate the estimation of the towfish motion parameters using the cross-correlation function of the beam data from consecutive pings of the sonar.

Principal Results:

It is shown that high resolution estimates of the along-track, across-track motion and the heading variation of the towfish can be obtained from the analysis of the sonar ping-to-ping cross-correlation function.

Military Relevance:

Sidescan sonars are used by the Canadian Navy for route survey applications. The Remote Minehunting System (RMS) also uses a sidescan sonar for mapping the seabed. The concepts discussed in this report will help in the precise georeferencing of sonar data. As well, synthetic aperture sonar techniques have shown potential in improving the resolution of sidescan sonar systems, thus improving the classification performance with respect to minelike objects. Such processing requires precisely estimating the relative motion of the towfish and thus the type of techniques described in this report are of interest for future work on synthetic aperture processing.

Future Research:

It is hoped to apply the techniques of this paper to obtain precise estimates of towfish motion and use these estimates to improve geocoding of data. Recently, DRDC-A has obtained the ability to record the complex envelope data at the individual staves of the Klein 5500 sidescan sonar and it is hoped that the techniques described in this paper can be used with this type of data for motion estimation and enhanced beamforming techniques. In the case of the complex beam or stave data, complex cross-correlations could be used.

Fawcett, John A.. 2003. Micronavigation of the Klein 5500 sidescan sonar using inter-ping beam correlations. DRDC Atlantic TM 2003-185 DRDC Atlantic.

Sommaire

Contexte

Pour géocoder avec une grande précision les données du sonar à balayage latéral, il faut des mesures précises du mouvement du poisson. Lorsqu'on souhaite combiner de façon cohérente les données relatives à la direction transversale ou à la direction longitudinale obtenues pour des impulsions successives (par exemple traitement des données du sonar à ouverture synthétique), on doit aussi disposer de mesures très précises du mouvement du poisson. Le présent rapport traite de l'estimation des paramètres de mouvement du poisson à l'aide de la fonction de corrélation croisée des données relatives à la direction transversale obtenues pour des impulsions consécutives du sonar.

Principaux résultats

On montre que des estimations à haute résolution du mouvement longitudinal et transversal ainsi que de la variation de cap du poisson peuvent être obtenues par l'analyse de la fonction de corrélation croisée d'impulsion à impulsion du sonar.

Importance militaire

Le sonar à balayage latéral est utilisé par la Marine canadienne pour les applications de levé de routes de navigation. Le système télécommandé de chasse aux mines (RMS) utilise aussi le sonar à balayage latéral pour cartographier le fond marin. Les concepts étudiés dans le présent rapport aideront à effectuer un géoréférencement précis des données sonar. De même, les techniques basées sur le sonar à ouverture synthétique ont montré qu'il est possible d'accroître la résolution des systèmes sonar à balayage latéral et d'améliorer ainsi l'efficacité de la classification des objets de type mine. Un tel traitement nécessite une estimation précise du mouvement relatif du poisson, de sorte que les techniques décrites dans le rapport présentent un intérêt pour les travaux futurs sur le traitement des données du sonar à ouverture synthétique.

Recherches futures

On compte utiliser les techniques décrites dans le présent rapport pour obtenir des estimations précises du mouvement du poisson et utiliser ces estimations pour améliorer le géocodage des données. Récemment, RDDC Atlantique a réussi à enregistrer les données d'enveloppes complexes pour les douves individuelles du sonar à balayage latéral Klein 5500 et on espère que les techniques décrites dans le présent rapport pourront être utilisées avec ce type de données aux fins de l'estimation du mouvement et de la mise forme améliorée des faisceaux. Dans le cas de données complexes relatives à la direction transversale ou à la direction longitudinale, des corrélations croisées complexes pourraient être utilisées.

Fawcett, John A.. 2003. *Micronavigation of the Klein 5500 sidescan sonar using inter-ping beam correlations* (Micronavigation du sonar à balayage latéral Klein 5500 à l'aide de corrélations des données relatives à la direction transversale d'impulsion à impulsion). RDDC Atlantique TM 2003-185. RDDC Atlantique.

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INTRODUCTION

A sidescan sonar provides one or more beams of data (the amplitude of the seabed backscatter) and the accurate positioning of these values (or georeferencing) with respect to the seabed requires accurate positional and attitude information for the towfish. The accuracy of the geocoding is particularly important for imaging small targets, when one wishes to removes distortions due to towfish motion. Also, if one wishes to use change detection methods in the case of a cluttered seabed, then a very accurate relative positioning of the objects on the seabed is important. In Reference 1 a method for imaging the seabed to sub-beamwidth resolution was described for the case of overlapping beams whose centres are displaced a fraction of a beamwidth. However, the determination of the precise positions of these beam centers is non-trivial and the methods of this paper could be applied in this case as well.

Some sonar systems record actual time series, or complex envelope series for the individual channels. In principle, such systems can perform inter-ping coherent processing to yield better beamforming results, perhaps by using the techniques of synthetic aperture. We (DRDC Atlantic) recently had our Klein 5500 Towfish Processing Unit (TPU) modified by Klein Inc. to allow us to record individual stave complex time series and, in the future, hope to investigate advanced beamforming techniques. In order to use coherent processing of such data over more than one ping, very accurate estimates of the towfish relative motion is required.

In this paper we will consider the estimation of motion parameters using the standard beam sets from the Klein 5500 sidescan sonar obtained from sea trials. In particular, we will consider the estimation of along-track motion, across-track motion and heading variation. The use of inter-ping correlations between channels of data (the time series) has been suggested by many authors as one of the main techniques for estimating the motion of a towfish between pings [see, for example 2]; the use of the beamformed amplitudes, as used in this paper, is perhaps not as common but has been discussed in [3].

THEORY

The Klein 5500 sidescan sonar is a multibeam sidescan sonar. It forms five beams, of approximately 10 or 20 cm resolution, on the port and starboard sides of the towfish. When the towfish is moving at slow speeds such as 4 knots, then 2 or 3 beams may be classed as redundant. That is, their coverage of the seabed overlaps the coverage from the previous beam set. The ping rate of the sonar is adjusted on the basis of the estimated tow speed in order that the overlap corresponds as near as possible to an integer number of beams. This is mainly for the ease of display, so that the image formed by using the "visible" beams will appear to be continuous.

In practice, because of pitch, altitude, heading, and speed variation the overlap between successive pings is not precisely an integer number of beams and the concept of redundant and visible beams is not exact. In this paper, we show that by cross-correlating successive beams sets it is possible to estimate the motion parameters of the towfish to a very accurate level. Of course, the towfish sensors measure some of these quantities directly or indirectly. However, often some sort of smoothing needs to be used for these measurements to yield acceptable results. Also, the resultant effective motion of the beamset with respect to the seabed is often a combination of these motions. Thus the direct measurement of the motion parameters using the data itself is useful.

There are a variety of motion parameters, which can be estimated. In Fig.1 we show a schematic of a towfish at 2 consecutive pings. If there was purely motion in the along-track direction then a portion of the Klein's 5 beams from Ping 1 should overlap a portion from Ping 2. In order to estimate this translation in a continuous fashion we divide each beam block into 3 subbeams, the central one which is the recorded beam. Between these beam centers (orange in the schematic of Fig.2) we interpolate linearly. The first and fifthteenth beams are set to the value of the first true and fifth true beam respectively.

We then suppose we select a subset of 4 beams (the interpolated beams) from the second ping. All possible sets of 4 consecutive beams from the first ping are cross-correlated with the set from the second ping. The maximum lateral shift is then in terms of 1/3 beamwidth. However, we refine this estimate further by using a quadratic interpolation of the maximum and the 2 neighbouring values to obtain a continuous estimate. The displacement (in cm.) between pings can be estimated from the formula

$$L = (I_2 - I_1) * 10/3. \qquad (1)$$

where I_2 is the index of the first beam (interpolated set) used from the second ping and I_1 is the determined index for the first set which maximizes the cross-correlation.

The along-track motion of the towfish with respect to the seabed is the net effect of 2 main components: the lateral translation of the towfish and the variation of the beams on the seabed due to the pitch variation of the towfish. The relative motion of the beams on the seabed due to pitch motion can be expressed by

$$\Delta_p = \Delta(h \tan(p)) \qquad (2)$$

where h is the altitude of the towfish, p is the pitch angle and Δ denotes the difference operator from one ping to the next.

In Fig. 2 we show a schematic diagram of two towfish positions in the case that the change in heading from one ping to the next is the angle ψ. It should be noted that ψ is shown as a significant angle in Fig.2 for illustrative purposes. In reality, this angle is usually very small. It is assumed in the following analysis that it is small enough so that over a fixed time window a set of beams from ping i will still cross correlate significantly with beams from ping i+1. In fact, there are sometimes pings for which the cross-correlation between the successive pings is relatively low and we attribute this to excessive ping or heading variation between pings. The average cross-range for the time segment of data considered is R. Figure 2 illustrates that the average of the beam displacements on the port and starboard sides (d_p and d_s) correspond to the along-track movement of the towfish, while the difference between the displacements on the port and starboard sides is related to the change in heading. In particular, for small values of ψ there is the relation

$$0.1 \ (d_s - d_p) / 3. \ = 2 R \ \psi \qquad (3)$$

The values of 0.1 are for the beamwidth of the Klein 5500 in high resolution mode and the factor 3 is the interpolation factor used.

Another towfish motion parameter which can be estimated using a cross correlation method is the ping-to-ping sway, (i.e., the relative across-track motion) of the towfish. This can be estimated by first determining the along-track motion and then cross-correlating the two beam time series, corresponding to the same along-track position, to determine the lateral motion.

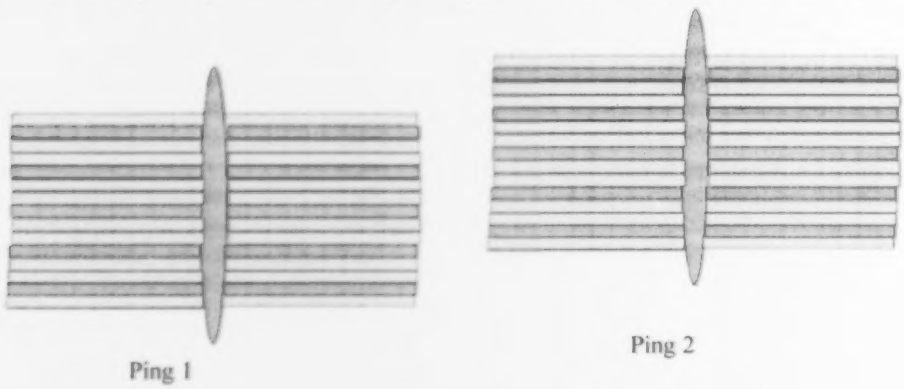

Figure 1 Schematic of beam interpolation scheme used – orange represents actual beam time series placed in the middle of the 10 cm (20 cm) beam. The grey beams are interpolated time series. Beams 1 and 15 are set to the values of beams 2 and 14. Two successive pings are shown with the towfish laterally displaced for display purposes.

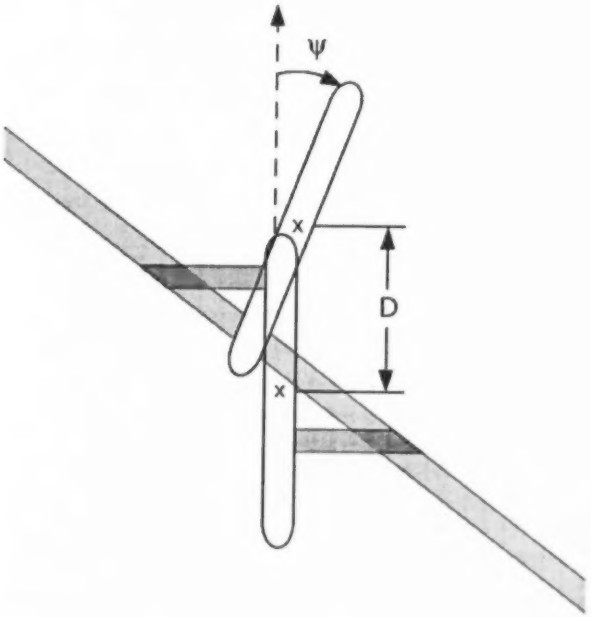

Figure 2. Schematic showing the towfish at 2 successive pings - the green band represents a beam from the second ping and the orange represents the maximizing beams from the first ping on the port and starboard sides. The parameter ψ is the change in heading (for illustrative purposes it is shown as being much larger than a realistic value) and D is the mean along-track distance from ping to ping.

DATA ANALYSIS

We consider 2 Klein sidescan sonar files from 2 sites near Halifax: Herring Cove and St. Margaret's Bay. These were collected using the 10-cm resolution setting of the Klein. We also tried the methods of this paper with the 20-cm setting; however, the results obtained with this setting seemed inferior to those with the 10-cm setting. It is not clear why. There is, of course, the fact that for the subtle variations in the beam displacement which are required for the accurate estimation of heading variation, that the finer resolution is important. It may also be that the 10 cm resolution beams naturally produce a greater amount of cross-correlation between overlapping sets and hence the resulting displacement and heading variation estimates are more accurate. In any event, we will consider only the 10-cm setting in this paper. The data was collected with a low amount of "despeckling" used in the Klein beamformer. The tow speed was approximately 4 knots, which meant that 2 or 3 beams were redundant at 4 knots, and for the time between pings, the along-track distance was typically 20 cm or 2 beamwidths. Of course, due to speed and pitch variation, this is only an approximate along-track displacement and it is the deviations from this distance that we hope to be able to accurately estimate.

Below we show the sidescan image of the seabed from Herring Cove – all the beams, including the redundant ones, are shown. A few small objects can be seen but, in general, the image appears quite uniform. However, even for this seabed there is a significant amount of

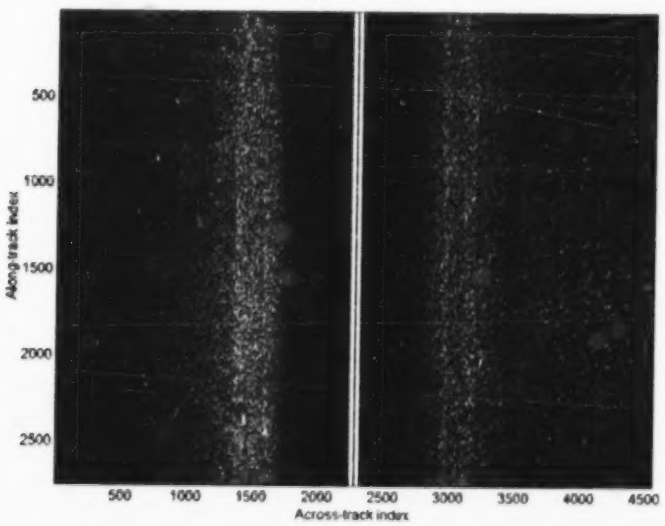

Figure 3 The Klein 5500 sidescan data from Herring Cove

structure in the echo time series.

In Fig.4 we show the 2 beam blocks from ping 2 and ping1 – the beam block shown for the first ping is the set which maximizes the cross-correlation with the block of ping 2. The time series have been smoothed in the across-track direction (time index) with a 3-point average. It can be seen that there are several features in the across-track direction and some variation with respect to the beam number.

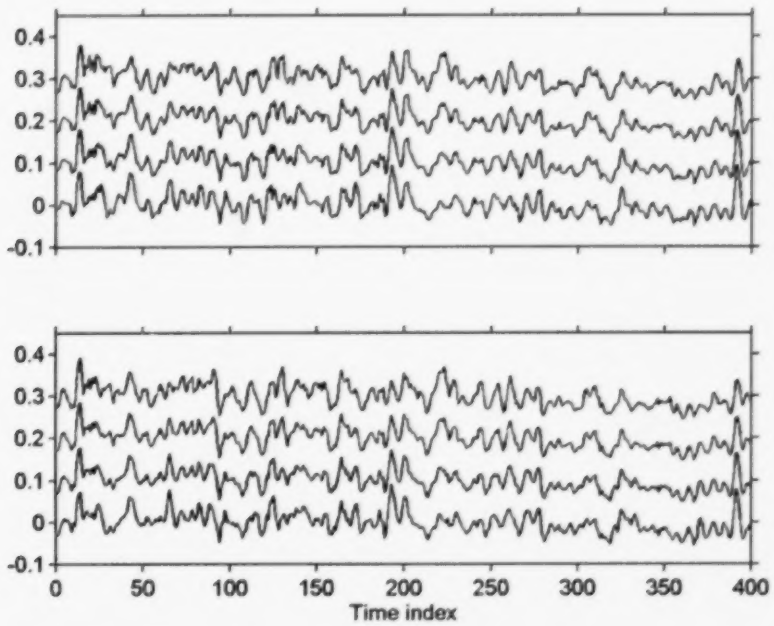

Figure 4 Two sets of interpolated beams for cross-range indices 800-1199; (top) ping 2 (bottom) ping 1 where the maximizing set for cross-correlation is shown for ping 1

In Fig.5 we show the cross correlation with the set of data in the top panel of Fig.4 as the various sets of 4 beams from ping 1 are cross correlated with it. As can be seen there is a peak at index 5 – this number can be further refined to some value between 4 and 5 by determining the maximum of the local quadratic function. In Fig.6, we show the results of estimating the maximizing beam block starting index when ping j is cross-correlated with the fixed block of ping j+1 for the entire file of data. The blue curve is the result of using the time indices 800-1199, with a mean cross-track range of about 30m and the red curve, using points 1200-1599 with a mean cross-track range of about 45m. Although there are some small differences between the curves, they are remarkably similar which gives us confidence in these estimates. In Fig.7 the same curves are shown for the starboard side. Once again the 2 curves are very similar. There are, however, more significant differences between these curves and those of Fig.6 (compare, for example, data points 200-300). It is these differences, which will yield information in the heading variation of the towfish.

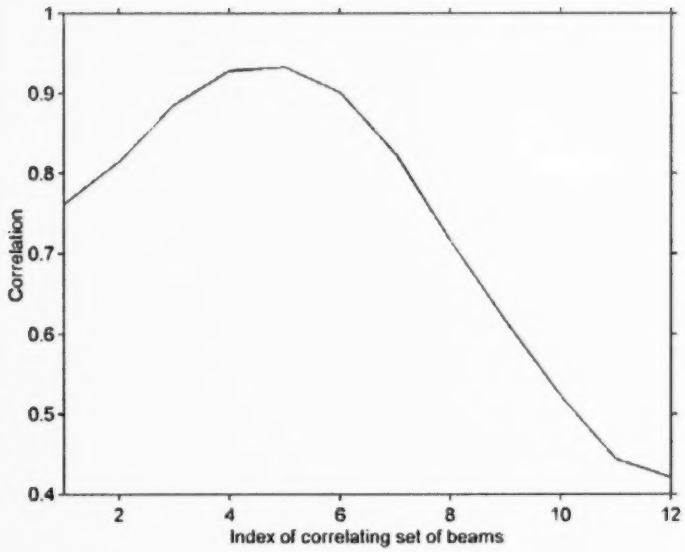

Figure 5 Cross-correlation between two beam blocks: a fixed set from ping 2 and varying the index of the blocks from ping 1 - this is for the starboard side.

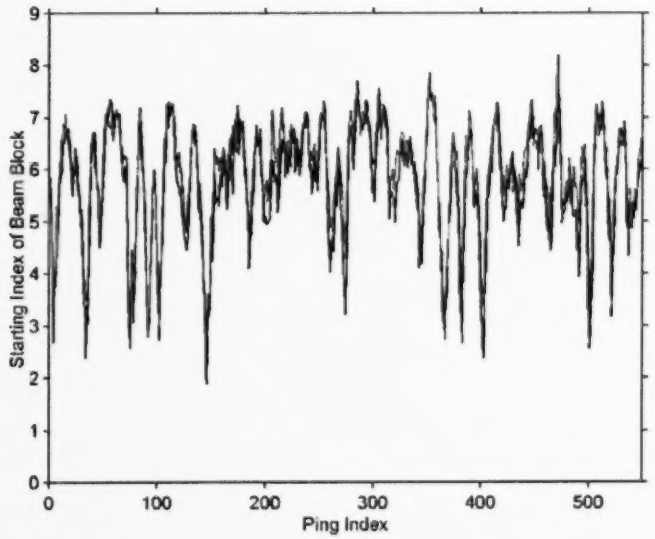

Figure 6 Maximizing index of beam block for ping-to-ping cross-correlation. The blue curve is obtained using points 800-1199 and the red 1200-1599 for the port side

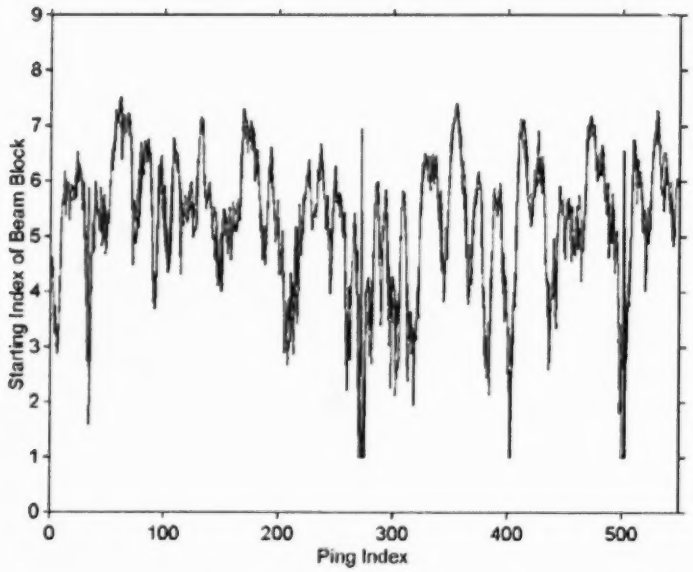

Figure 7 Maximizing index of beam block for ping-to-ping cross-correlation. The blue curve is obtained using points 800-1199 and the red, 1200-1599 for the starboard side.

Taking the mean of the blue curves from Figs.6 and 7, (similarly for the red curves) the resulting average can be translated into an along-track displacement estimate. Assuming that for this data set, that the average motion is approximately 20cm, we show in Figures 8 and 9 the estimated along-track motion (with the 20 cm subtracted out) using first the average of the starboard and port data for the points 800-1199 and then for points 1200-1599. The blue curves are the displacements along the seabed by considering the towfish pitch variation of Eq.(2). As can be the curves correlate nicely with this pitch variation. The pitch variation is not the only factor affecting the along-track displacement; there are also variations in the tow speed. Although the ping rate is adjusted on the basis of the ship speed to attempt to make the displacement an integer number of beams (in this case, 2) this is not perfect, so that the average advance of 20 cm is only approximate. Because of this, we do not expect the direct measurement of displacement through the correlation techniques to agree exactly with the pitch variation.

Using Eq.(3) we can use the set of inner data for port and starboard sides to estimate the heading variation from ping to ping. This variation is then integrated (a running sum) to yield the estimated heading of the towfish over time. We also do this for the outer sets of data points. The starting heading is undefined using this method. In the results shown below this value was adjusted independently for the 2 curves to yield good overall agreement with the towfish heading data. This towfish heading was uncalibrated at the time of recording; we have approximately calibrated these values using a formula due to Anna Crawford [4].

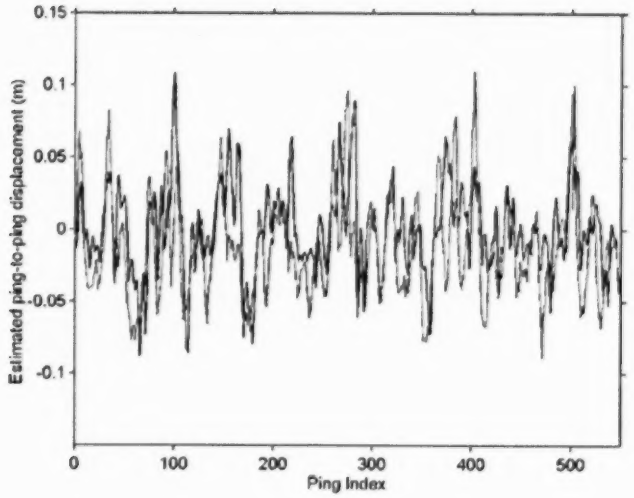

Figure 8 Estimated along-track motion (with 20 cm subtracted out) using the cross-correlation method (red) and the motion estimated from pitch variation (blue) using the points 800-1199.

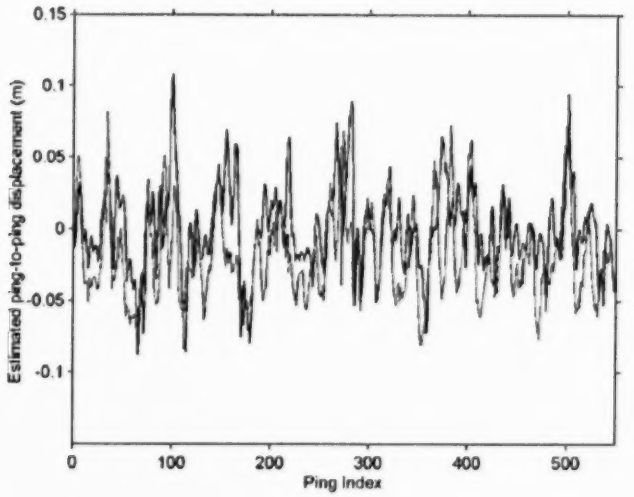

Figure 9 Estimated along-track motion (with 20 cm subtracted out) using the cross-correlation method (red) and the motion estimated from pitch variation (blue) using the points 1200-1599

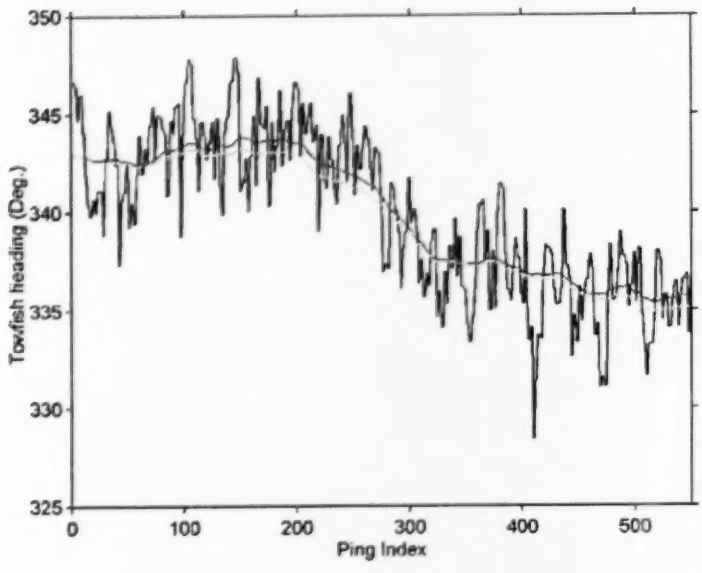

Figure 10 Towfish heading (approximately calibrated) (blue) with estimated heading from correlation using inner port/starboard data (red) and outer data (green)

The second example we consider is from a different site: St. Margaret's Bay. The sidescan image is shown below in Fig.11. The seabed is fairly benign although there are boulders in the image and a closer examination reveals a significant scour mark. As before we use the indices which maximize the cross-correlation between successive beam blocks to estimate the along-track motion of the towfish. In Figs 12 and 13 the estimated displacements (with 20 cm subtracted off) are shown in red for the inner set of data (points 800-1199) and the outer set of data (1200-1599) with the variation derived from the pitch variation shown in blue. As can be seen the cross—correlation curves (red) correlate nicely with the pitch estimates, except for the 2 peaks of large pitch variation. The sets of curves from the inner and outer data sections are very consistent with each other.

In Fig.14 we show the heading variation as measured from the towfish (blue) with the estimated heading variation from the inner (red) and outer (green) estimates. Once again the estimates follow the trend of the towfish heading variation nicely.

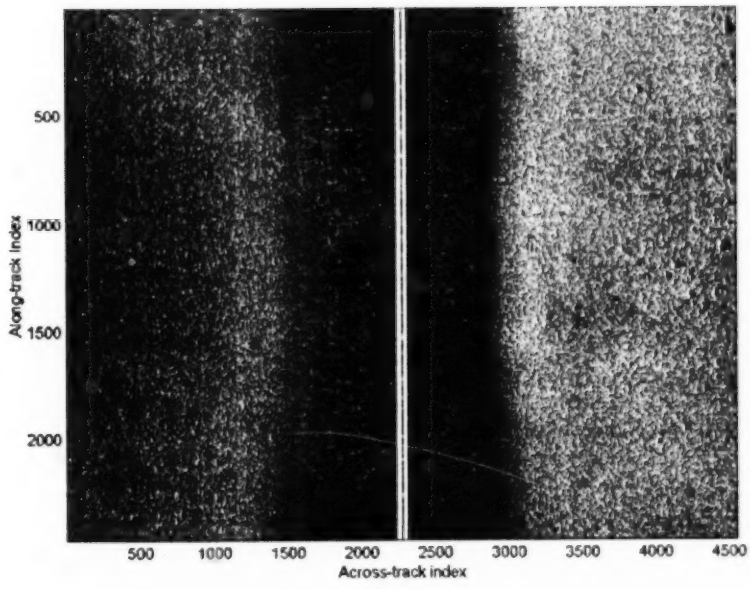

Figure 11 Sidescan image from St. Margaret's Bay

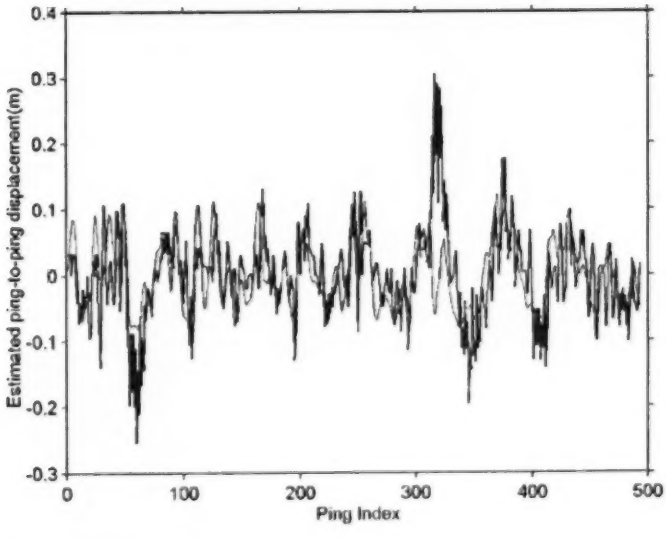

Figure 12 Estimated along-track motion (with 20 cm subtracted out) using the cross-correlation method (red) and the motion estimated from pitch variation (blue) using the points 800-1199.

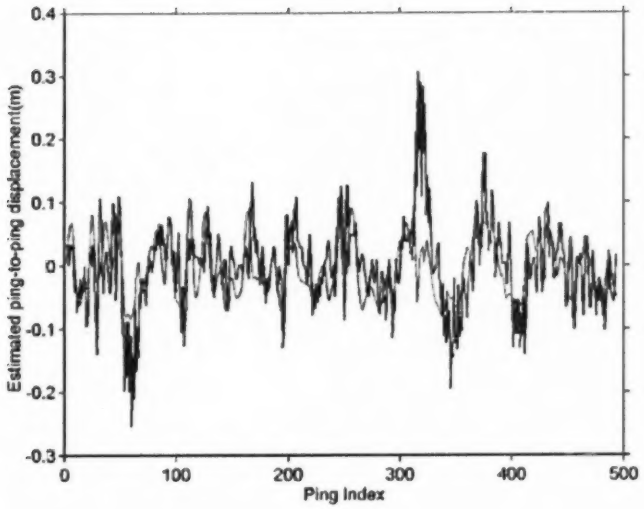

Figure 13 Estimated along-track motion (with 20 cm subtracted out) using the cross-correlation method (red) and the motion estimated from pitch variation (blue) using the points 1200-1599

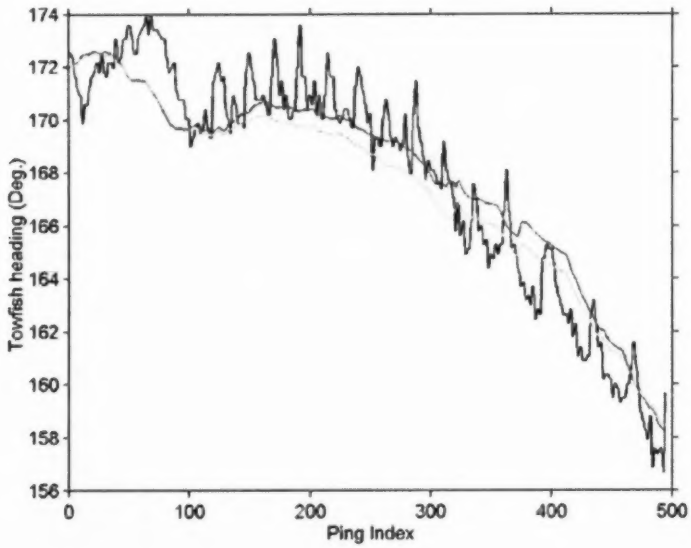

Figure 14 Towfish heading (approximately calibrated) (blue) with estimated heading from correlation using inner port/starboard data (red) and outer data (green)

Thus far, we have considered the estimation of the along-track motion and heading variation of the towfish. Another important motion parameter is the relative across-track motion or sway of the towfish. There are a variety of factors which create the effective sway. The variation of the towfish altitude, will change the time index which correspond to a fixed point on the seabed. The roll of the towfish, and of course any actual lateral motion of the towfish will also contribute to the sway. For the following estimates of sway, we first extract two vectors of data from the beam blocks from 2 successive pings which are believed (from the along-track motion estimation) to correspond to each other (we choose the first beams from each beamblock). These vectors are then resampled at a time spacing spacing of 10 times the original using cubic spline interpolation. These vectors are then cross-correlated with each other and the maximizing index obtained for each pair of pings. A quadratic interpolation is then used to refine this estimate further. It is not clear how accurately we can estimate the lateral motion from the cross correlation of the 2 time series. This depends upon the SNR and structure of the signals. In Fig.15 a typical cross correlation plot for the 2 vectors is shown, where the index 3990 would represent a zero lateral shift between the pings. In Figs.16 and 17 we show the resulting ping time history of estimating the lateral displacement (sway) for each pair of successive pings using first the inner set of data and then the outer set.

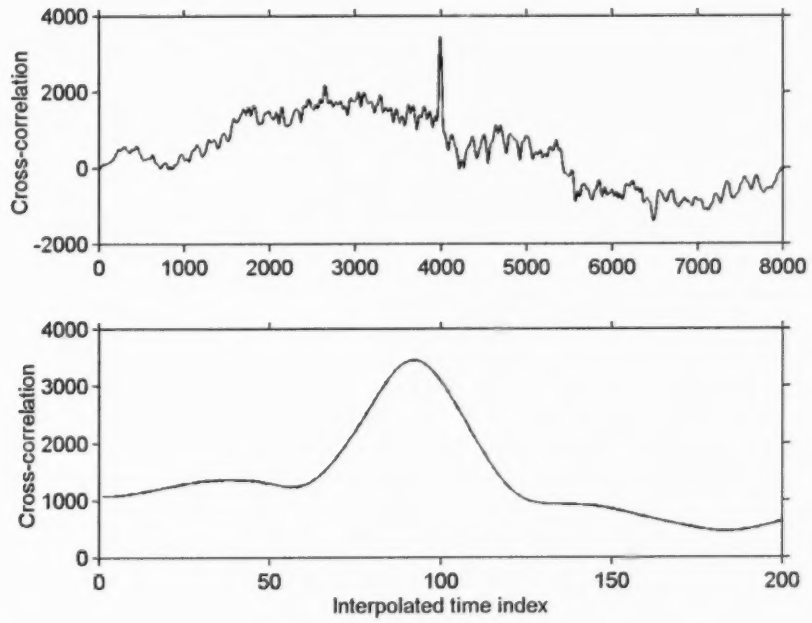

Figure 15 The cross-correlation between the time series (400 point section reinterpolated by a factor of 10) and a zoom of the peak region

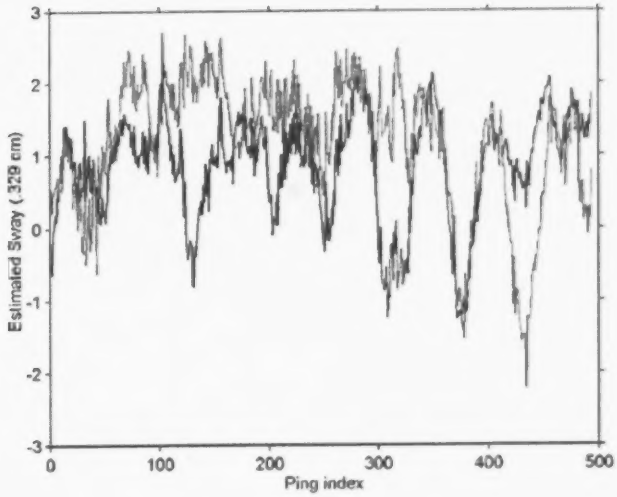

Figure 16 Estimated sway in terms of .329 cm units - using the port beams (blue) and starboard beams (ref) for data points 800-1199

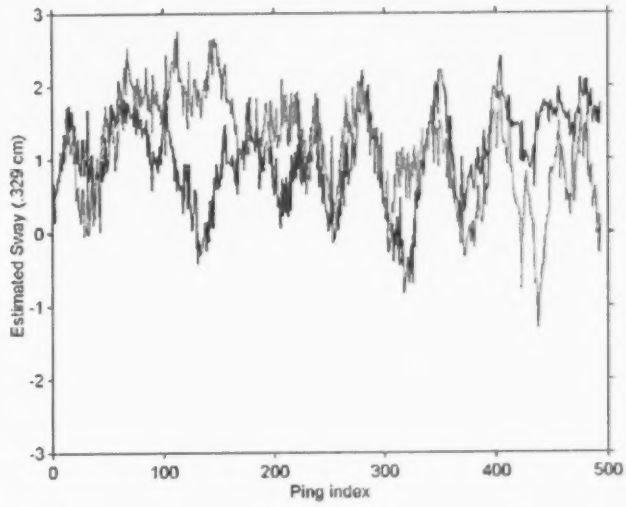

FIgure 17 Estimated sway in terms of .329 cm units - using the port beams (blue) and starboard beams (red) for data points 1200-1599

The curves shown in Figs.16 and 17 result from using a 11-point smoothing of the original estimates (also the data used was initially smoothed by a 3-point filter in the across-track direction). The curves have some definite structure. It is interesting to note that there are regions where the port and starboard curves agree with each other very closely and other regions where they differ. This is probably related to the mechanism which produced this lateral movement. The only mechanism (at least, as far as the author knows) which would produce the same movement on both the port and starboard sides would be an altitude change. Lateral motions of the towfish or change in roll should produce an anti-symmetric motion. The set of curves for the outer set of data, Fig.17, agree well with those from the inner set. There are some differences, particularly for the starboard side at about datapoint 300 (which is also where there is a large pitch variation in Fig.13), but overall the agreement with those Fig.16 is encouraging. It would appear that although the estimate of the sway on a sub-centimetre scale may not be accurate on the basis of a single ping, it may be possible to obtain accurate estimates if one assumes that this parameter should vary somewhat smoothly over the ping history.

SUMMARY AND DISCUSSION OF RESULTS

It has been shown in this report that the cross correlation between the consecutive beams of a sidescan sonar can be used to estimate various towfish motion parameters. This technique is applicable in the case that the sonar is towed slowly enough that there is overlapping, or redundant, beam coverage of the seabed. For this study we used the 10-cm setting for the Klein. It was shown that it was possible to obtain high resolution estimates of the towfish along-track motion, across-track motion and heading variation using this technique. The results were consistent with the direct pitch and heading measurements of the towfish sensors. However, unlike the measurements made by the towfish sensors, the estimates obtained by the cross-correlation method are those parameters values which directly optimize the cross-correlation between consecutive beam sets (i.e., the estimates are derived from the data itself). It is hoped that these motion estimates will be useful for precise geocoding. In the future, it is also hoped that these type of estimates can be used to improve multi-ping coherent beamforming processes for the Klein 5500, now that DRDC Atlantic has the ability to collect the complex envelope data at the individual staves.

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4. Anna Crawford, private communication, 2003.

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In this report, the cross correlation between the beams of sidescan sonar data from consecutive pings is investigated. The along-track and across-track shifts which maximize this cross-correlation yield high resolution estimates of the along-track motion and the sway of the towfish. The difference of the estimates for the port and starboard sides can be used to estimate the towfish heading change. This technique is examined using data from the DRDC-A Klein 5500 sidescan sonar and it is shown that the estimates, which are obtained in this manner, are consistent with direct sensor measurements of the towfish heading and pitch.

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